Six[th] International Conference of
Seismology and Earthquake Engineering
16-18 May 2011 Tehran, Iran

SIMPLIFIED NUMERICAL ANALYSIS OF BOND DEGRADATION OF FRP-MASONRY SYSTEMS FOR DURABILITY PURPOSES

B. Ghiassi[1], G. Marcari[2], D.V. Oliveira[3], P.B. Lourenço[4]

[1] *PhD Candidate, ISISE, University of Minho, Portugal, bahmanghiassi@civil.uminho.pt*
[2] *Assistant Professor, ISISE, University of Minho, Portugal, marcarigia@civil.uminho.pt*
[3] *Assistant Professor, ISISE, University of Minho, Portugal, danvco@civil.uminho.pt*
[4] *Professor, ISISE, University of Minho, Portugal, pbl@civil.uminho.pt*

ABSTRACT

Fiber Reinforced Polymers have become a popular material for external strengthening of masonry structures in the last years, but still further investigations are needed in order to develop appropriate design procedures. Investigating the behaviour and performance of retrofitted masonry elements with FRP composite sheets requires considering different mechanisms and issues. Among them, the most important is the bond between FRP and substrate due to its function in transferring the stresses from the FRP sheets to the structure. Hence, conducting experimental and numerical studies for understanding the bond and its degradation mechanism due to environmental exposure is a critical subject in predicting the performance of strengthened structures. As the available information on the durability of bond in FRP retrofitted masonry elements is still rare, conducting extensive experimental and numerical studies for characterizing this phenomenon is an important issue. This paper presents a simple degradation model into an available interface model for investigating the bond degradation in retrofitted masonry elements. For this reason, at first the interface model is calibrated with the experimental tests performed at University of Minho, and then the degradation of the bond is implemented in this model through a simplified approach.

Keywords: Durability, bond behaviour, numerical modelling, FRP-masonry

1. INTRODUCTION

The experience of past earthquakes has shown that a great number of masonry structures are vulnerable to seismic actions and moderate to strong earthquakes can devastate them resulting in massive death of people and extensive losses. Therefore, different strengthening techniques have been investigated for improving the seismic performance of these structures. Among these techniques, Fiber Reinforced Polymers have become a popular material for external strengthening of masonry structures in the last years because of their advantages in terms of structural performance improvements and low installation costs. Although the effectiveness of this strengthening technique has been studied fairly in concrete structures, the available information for masonry components is still lacking.
The effectiveness of this strengthening technique is highly dependent on the interfacial bond between FRP and substrate which shows the importance of understanding and characterization of this mechanism. Different experimental and numerical studies have been conducted in the last years for studying the bond behaviour in FRP strengthened concrete members ([1-7]) but attention to the masonry structures has been

raised very recently (e.g. [8-11]). Experimental investigations have been performed using different test set-ups such as single shear bond, double shear bond, or beam tests for concrete strengthened members and as far as an accepted experimental method for FRP strengthened masonry elements is not available yet, same test set-ups have been used for them ([8-10, 12]). In case of numerical modeling, there is still a lack of information on suitable methods applicable for modelling the bond behaviour. Besides, most of the studies have been performed to simulate debonding behaviour of FRP strengthened concrete elements (e.g. [2, 3, 13]), and few research can be found on FRP -masonry components (e.g. [8, 11]). These models usually follow two main approaches. In the first approach, the bond behaviour is modelled by using a zero thickness interface element between FRP and substrate (e.g. [2, 13]). The properties of the interface elements can be obtained through experimental tests or using available bond-slip laws. In this case all the nonlinearities are usually concentrated in the interface and an elastic behaviour is assumed for the other parts. These models are not truly predictive, although they may be used with tests to verify or identify the interfacial behaviour [3, 11]. In the second approach, besides using interface elements, the debonding is directly simulated by modelling the cracking and failure of all the constituents according to a meso-scale model [3]. The advantage of this model is that it provides a framework for investigating the local stresses and processes which usually encompass the debonding phenomenon [11]. On the contrary, the role of the interfaces whose properties may be susceptible to environmental conditions (such as temperature and humidity changes) is neglected. Characterization of the concrete or masonry layer near the epoxy resin layer is also an important issue in obtaining suitable results in this modelling approach.

Another important aspect that should be considered in this strengthening technique is the durability of interfacial bond under environmental conditions. Although previous studies have shown the advantages of using FRP composites in strengthening the structures, the long-term performance of them and more importantly the bond behavior between the FRP composite and the structural support, are still unknown. The structures are usually subjected to different environmental conditions such as freeze-thaw, temperature and moisture variations during their service life that may affect performance of the structure, strengthening material, adhesive, and FRP-substrate interface. The available information on degradation of bond due to environmental conditions is still rare either for FRP-concrete (e.g. [14-17]) or FRP-masonry components (e.g. [18-20]). In general, it has been observed that FRP materials can tolerate environmental conditions with small reductions in mechanical properties [14], while the substrate and adhesive properties maybe highly deteriorated [21]. Temperature variations and moisture exposure conditions have already been found to reduce bond shear strength and peak slip. Moreover force-displacement diagrams of the bond behaviour showed a non-linear trend at a lower applied force. These observations have been usually attributed to thermal incompatibility, extensive moisture plasticization of the polymer adhesive and additional breakage of interfacial bonds. As far as the performed studies consist of a wide range of different test specimens, environmental conditions, and FRP materials, quantification of the observed damage and comparing the available results is difficult. Therefore performing comprehensive experimental and numerical studies for characterization of the bond degradation in these elements is of crucial importance.

This paper presents a preliminary step of a comprehensive ongoing project at the University of Minho attributed to the investigation of FRP-masonry bond degradation due to temperature and moisture variations. The paper presents numerical modelling of the interfacial bond in FRP-masonry bricks using interface elements. The applicability of the adopted model has been validated by comparing the analysis results with single shear bond test results. The effects of bond environmental degradation in the global and local behaviour of the FRP bonded masonry brick have been also investigated. The environmental degradation is modelled simply by modifying the adopted bond-slip law based on the experimental observations available in technical literature.

2. NUMERICAL MODELING OF BOND BEHAVIOR

Fracture in FRP-masonry elements under pull-out or peeling stresses usually occurs in the masonry near the interface, since the tensile strength of brick masonry is lower than that of the epoxy resin. As the thickness of the debonded masonry has been observed to be very small in comparison to the unit thickness (depending on the unit properties), the damage can be considered as interfacial debonding, using interface elements between FRP and masonry unit (Figure 1). Usually in this modelling approach, it is assumed that the FRP sheet and brick behave linearly and the nonlinearity of the system will be concentrated in the interface region. Accuracy of the results in this modelling approach depends highly on the adopted bond-slip law for the interface element. Although the interfacial behaviour has been the subject of many studies and different bond-slip laws have been proposed for FRP-concrete components (e.g. [2, 22, 23]), this information for FRP-masonry is still lacking.

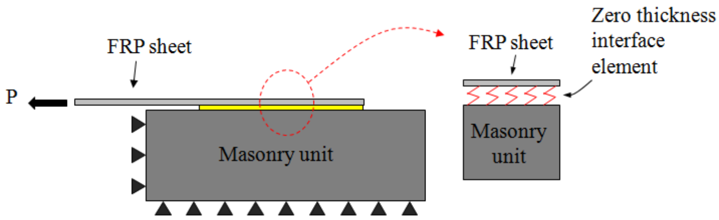

Figure 1. *Modeling the bond behaviour in single shear bond test*

2.1 Finite element modelling

The numerical analysis has been conducted following the described approach (Figure 1) by developing a 2D finite element model in the FE code DIANA 9.4 [24]. The adopted mesh includes eight-node plane stress elements (labelled as CQ16M in DIANA) for representing the masonry unit, three-node beam elements (labelled as CL9BE in DIANA) for FRP sheet, and six-node interface elements (labelled as CL12I in DIANA) for FRP-masonry interface. The constraints and loading conditions is applied to the model as shown in Figure 1. The masonry brick and FRP sheet are modelled using a linear elastic material and for the interface element a multi-linear bond slip model is adopted. An incremental displacement load is applied to the end of the FRP sheet for simulating the test conditions and particular attention has been made in choosing correctly the incremental steps during the nonlinear analysis. The accuracy of the adopted model is verified by comparing the analysis results with experimental data in the next section.

2.2 Model verification

For validation of the adopted model, single shear bond tests performed at the University of Minho on masonry bricks strengthened with CFRP and BFRP sheets are selected. The application of the FRP sheets was performed following a wet layup procedure. For investigating the bond behaviour, single shear bond tests were performed on the strengthened specimens by using a closed-loop servo-controlled testing machine. The tests were carried out in a displacement control condition, by imposing constant displacements of 5μm/min at the end of the FRP strip, while the resulting load was measured by means of a load cell. Electrical strain gauges were used to capture the strain distribution along the FRP sheets. The details of the tested specimens and the material properties are shown in Figure 2 and Table 1, respectively. Totally, six specimens for each type of FRP were tested. The obtained experimental force-displacement curves for all the specimens strengthened with CFRP and BFRP sheets are shown in Figure 3. The strain distributions along the bonded length are also shown in Figure 4 for one of the tested specimens for each FRP type. It can be seen that the specimens showed nonlinear and ductile bond behaviour on the contrary to the usual observed behaviour in FRP strengthened concrete elements. The observed failure mode in the specimens was delamination of the FRP sheet with a thin uniform layer of brick (approximately 1 mm) which can be described by the good mechanical properties of the masonry bricks.

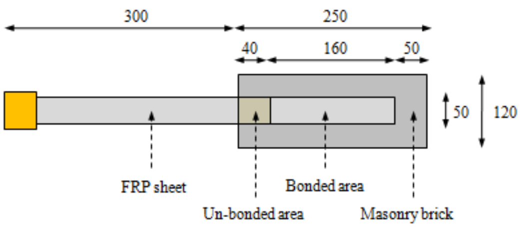

Figure 2. *FRP-masonry specimens details*

Table 1. *Characteristics of materials*

Material	E (MPa)	f_c (MPa)	f_t (MPa)	ε_{max} (%)
Brick	10868	19.76	-	-
GFRP	77160	-	1350	1.86
BFRP	86090	-	1498.96	1.74

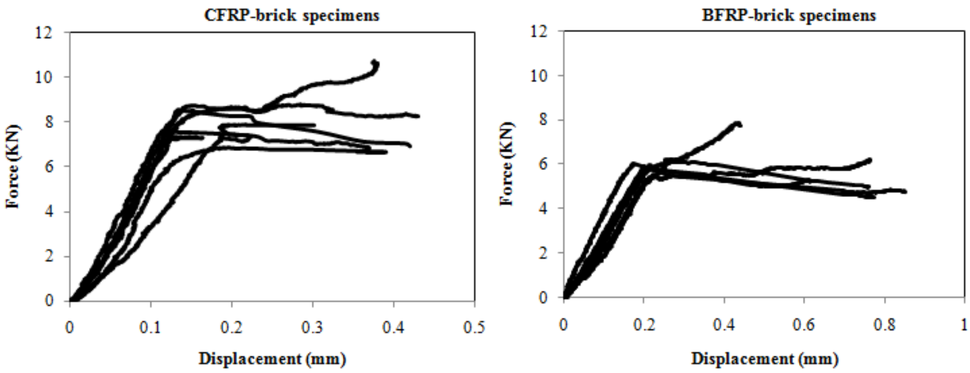

Figure 3*. Experimental load – relative displacement curves*

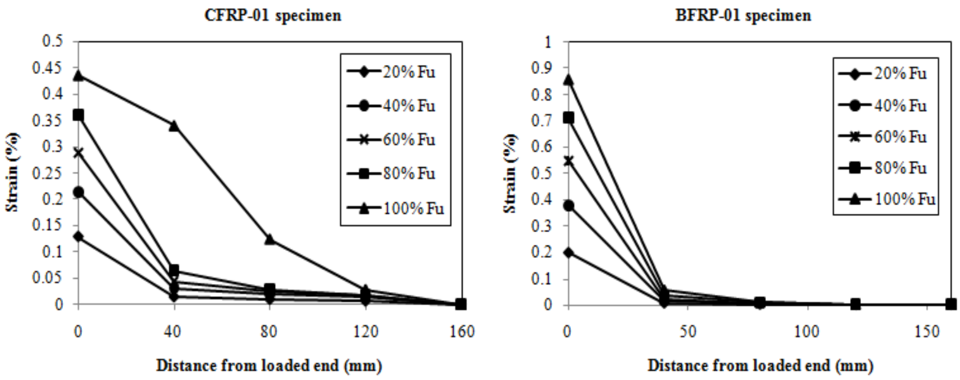

Figure 4*. Experimental strains distribution along the bonded length*

The selected tests are simulated in the FE code DIANA 9.4 [24] following the procedure described in the previous section. The bond behaviour is modelled using zero thickness interface elements by adopting a multi-linear bond slip law considering the local bond behaviour of the specimens (Figure 5). The local bond behaviour can be obtained from the strain distribution along the bonded length using analytical procedures. The bond-slip law parameters used in the numerical analysis are shown in Table 2 for both CFRP and BFRP strengthened specimens. These are obtained by performing a parameter study to have the best local and global results in comparison with the experimental results.

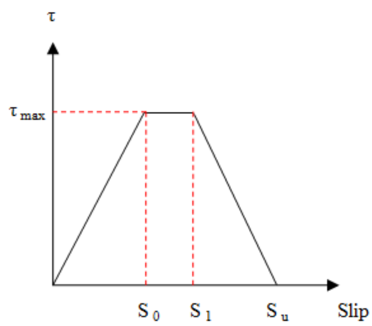

Figure 5*. Adopted bond-slip model*

Table 2*. Bond-slip law parameters*

Specimen	τ_{max} (MPa)	S_0 (mm)	S_1 (mm)	S_u (mm)
CFRP-Masonry	1.8	0.04	0.09	0.35
BFRP-Masonry	1.8	0.02	0.15	0.3

The results obtained from the numerical analysis are compared with the experimental ones in Figures 6 and 7 in terms of global load-displacement curves and local strain distributions along the bonded length, respectively. The good agreement between the numerical and experimental results is the evidence of the capability of the adopted numerical modelling method and bond-slip constitutive model. This good agreement stands even in high nonlinear ranges of bond behaviour.

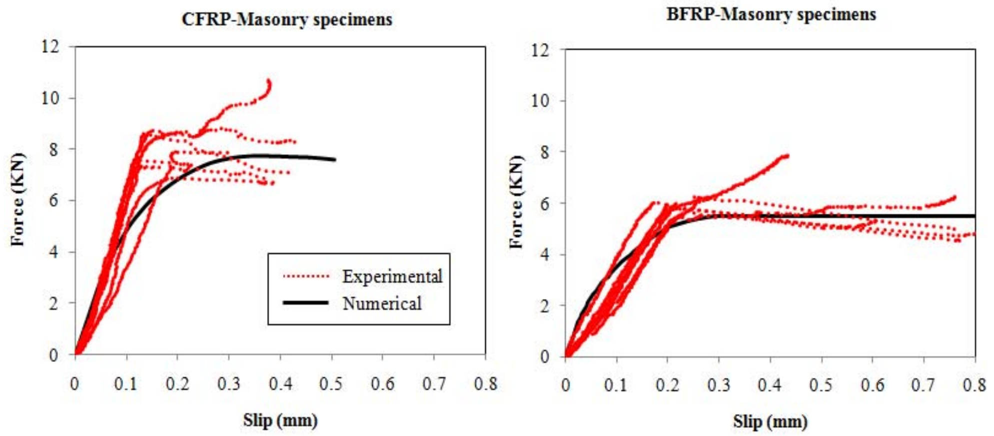

Figure 6. *Comparison of numerical and experimental load-displacement curves*

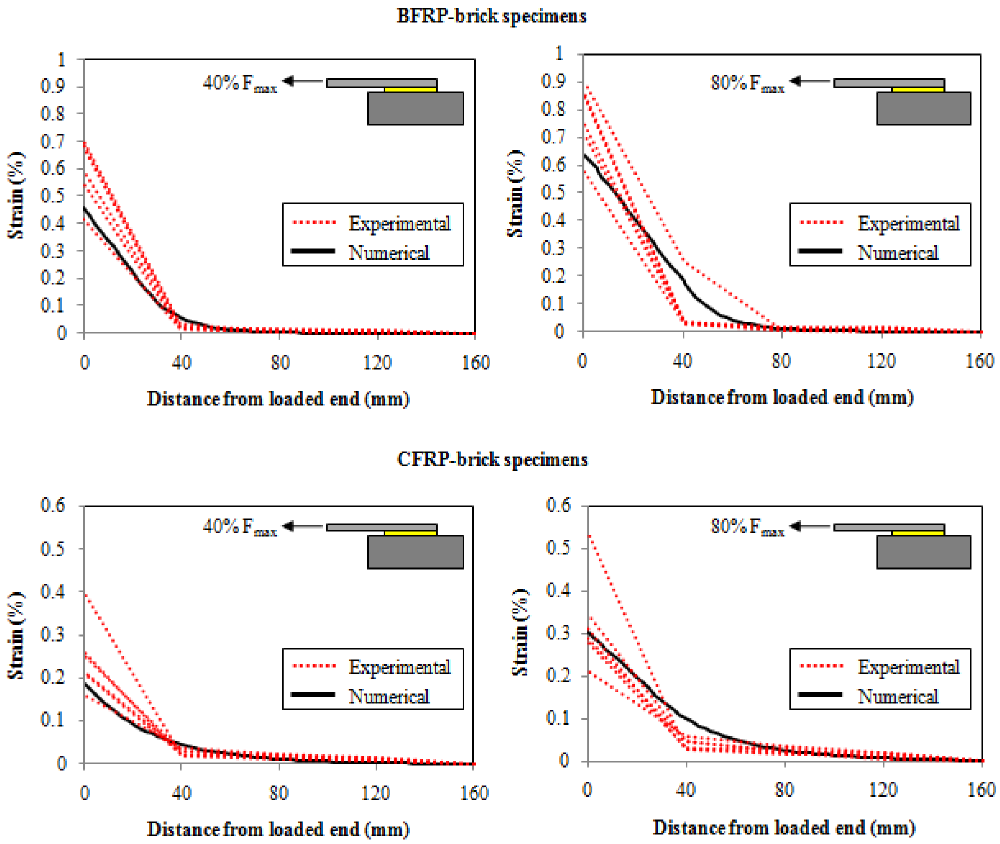

Figure 7. *Comparison of numerical and experimental strain distributions*

3. DEGRADATION MODELING

The available experimental information on interfacial bond degradation in FRP-concrete or FRP-masonry components due to environmental conditions is still rare. As performing real exposure tests needs years to be completed, these tests are usually performed in an accelerated form by increasing the intensity of the exposure or the rate of exposure cycles. The environmental conditions usually consist of temperature

exposure, moisture exposure, alkaline environment exposure, and UV exposure.
The tests performed on the FRP-concrete components have shown that FRP materials can tolerate environmental conditions with small reductions in mechanical properties [14], while the substrate and adhesive properties maybe deteriorated significantly [21]. Temperature variations and moisture exposure conditions have already been found to reduce the bond shear strength and peak slip, while a non-linear bond behaviour is observed at a lower applied force [25]. These observations have also been reported in the few studies that have been conducted on FRP-masonry systems such as the tests performed by Desiderio and Feo [19], Briccoli Bati and Rotunno [20], and Aiello and Sciolti [18]. While accelerated tests are still crucial to be performed comprehensively on FRP-masonry systems for understanding the bond degradation mechanisms, establishing an appropriate link between accelerated tests and real exposure conditions is mandatory by the aim of service life modelling procedures or performing real test exposures.
As far as the available information on the bond degradation mechanism is still lacking, the degradation in interfacial bond due to environmental conditions has been considered by decreasing the bond strength and stiffness in the adopted bond-slip model. These reductions are expected to occur due to environmental effects as described above. Moreover, the reductions have been applied in two stages representing two levels of degradation, called low and high degradation levels (Table 3).
The effects of two degradation levels on the local and global bond behaviour are studied on the CFRP strengthened specimens by performing numerical analysis using the reduced values for the adopted bond-slip model. The obtained load-displacement curves and strain distributions in the degraded specimens are shown in Figures 8 and 9. The obtained results show some important effects of environmental degradation on the performance of FRP bonded masonry elements. Reduction in capacity and stiffness of the specimens in the global behaviour was found in the load-displacement curves (Figure 8). In terms of local behaviour, it is shown that not only the strain distribution along the bonded length has changed, but also the effective bond length increased in accordance with experimental studies.
The environmental degradation, as can significantly affect the performance of the strengthened structures, should be considered in the design procedures. In this regard, some guidelines such as CNR/DT 200 [26] has proposed some reduction factors to be applied on mechanical properties of the composite materials but as there is no extensive experimental or numerical background behind these reduction factors, the reliability of them is under question. Not only comprehensive accelerated tests should be performed for this aim, but also an effort should be made to establish a link between accelerated test result and real exposure conditions.

***Table 3**. Modelling the bond environmental degradation*

Degradation level	Reduction factor	Reduced parameters
Low degradation	20%	τ_{max}, k
High degradation	50%	τ_{max}, k

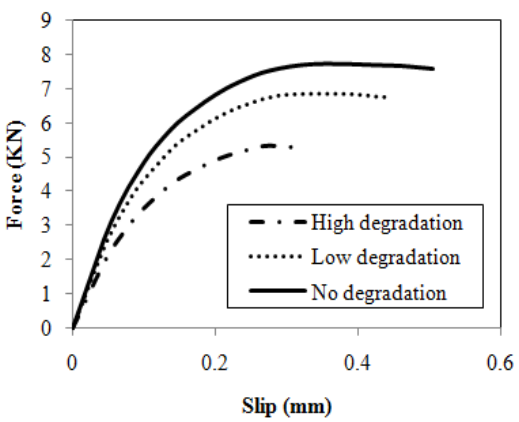

***Figure 8**. Load-displacement curves of the degraded CFRP strengthened specimens*

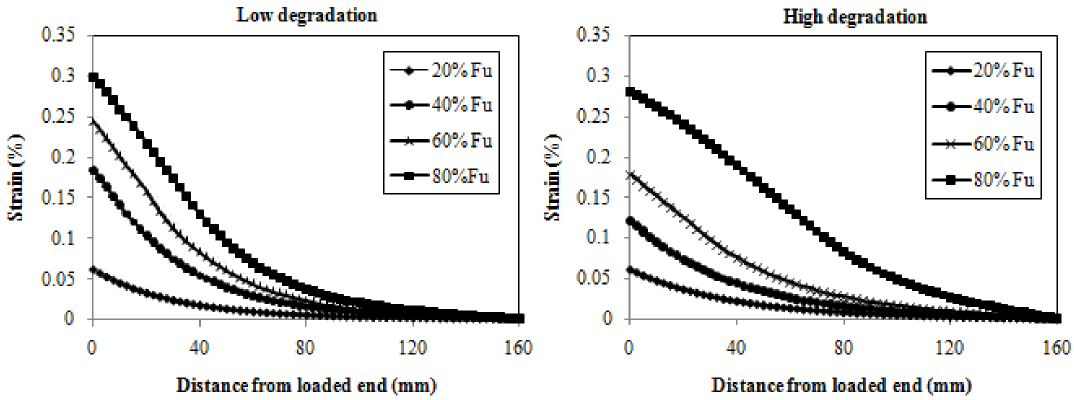

Figure 9. *Strain distributions along the bonded length after degradation (CFRP specimen)*

4. CONCLUSIONS

Bonding FRP sheets/laminates externally to existing RC or masonry members has become a reliable strengthening technique in terms of increasing the performance of the structure. The bond behaviour in this strengthening technique is a very important aspect and affects the performance of the strengthened structure directly. In this regard, experimental and numerical studies on the bond behaviour have been the subject of many research projects in the last years for understanding the bond mechanism and developing appropriated constitutive models for this phenomenon. In FRP-strengthened masonry components, reliable information on the bond behaviour is still lacking and the development of bond-slip models and appropriate numerical modelling approaches are under investigation. Another important aspect in this area is the durability and degradation mechanisms of bond due to environmental conditions which also need to be comprehensively studied.

In this paper a numerical modelling approach has been adopted to model the bond behaviour of the masonry strengthened bricks by using interface elements representative of the interfacial behaviour. The adopted model has been validated by comparing the analysis results with the single shear bond tests performed at the University of Minho. The good agreement between the analysis and experimental results is obtained in terms of global and local behaviour even in the highly nonlinear ranges of behaviour (strain distribution in 80% of the peak load). This agreement shows the reliability of the adopted method and good selection of the bond-slip model in this study.

Then, as far as the available information on the bond degradation mechanism is still lacking and environmental effects on the bond performance have not been quantified yet, the effects of bond degradation on the local and global behaviour of the strengthened specimens have been studied through applying reductions on the bond strength and stiffness in the adopted bond-slip model. It has been shown that the environmental degradation affect the global behaviour in terms of reduction in capacity and stiffness of the specimens, and the local behaviour by increasing the effective bond length. These two important effects need to be considered in the design procedures which can be done by quantifying the environmental degradation through performing comprehensive experimental accelerated tests. Moreover it is required to establish reliable link between the accelerated test results and real exposure conditions.

5. ACKNOLEDEGMENTS

This work was partly funded by project FP7-ENV-2009-1-244123-NIKER of the 7th Framework Programme of the European Commission Project which is gratefully acknowledged.

6. REFERENCES

1. **Yao, J., J.G. Teng, J.G., Chen, J.F.** (2005). "*Experimental study on FRP-to-concrete bonded joint",* Journal of Composites: Part B, **36**(2): p. 99-113.
2. **Dai, J.G., Sato, Y., Ueda, T.** (2005). "*Development of the nonlinear bond stress-slip model of fiber reinforced plastics sheets-concrete interfaces with a simple method",* Journal of Composites for Construction, 9(1): p. 52-62.

3. **Lu, X.Z., Ye, L.P., Teng, J.G., Jiang, J.J.** (2005). "*Meso-scale finite element model for FRP sheets/plates bonded to concrete",* Engineering Structures, 27(4): p. 564-575.
4. **Bizindavyi, L. and Neal, K.W.** (1999). "*Transfer lenght and bond strength for composites bonded to concrete",* Journal of Composites for Construction, 3(4): p. 153-160.
5. **Brosens, K. and Gemert, D.V.** (1999). "*Anchorage design for externally bonded carbon fiber reinforced polymer laminates"*, ACI, SP 188-56, p. 635-641.
6. **Chajes, M.J., Finch, W.W., Januszka, T.F., Thomson, T.A.** (1996). "*Bond and force transfer of composite material plates bonded to concrete",* ACI Structural Journal, 93(2): p. 208-217.
7. **Pellegrino, C., Tinazzi, D., Modena, C.** (2008). "*Experimental study on bond behavior between concrete and FRP reinforcemen",* Journal of Composites for Construction, 12(2): p. 180-189.
8. **Grande, E., Imbimbo, M., Sacco, E.** (2010). "*Experimental investigation on the bond behavior of CFRP laminates glued on clay bricks: Experimental and numerical study*", Journal of Composites: Part B (in press).
9. **Aiello, M.A., Sciolti, S.M.** (2005). "*Bond analysis of masonry structures strenghtened with CFRP sheet",* Construction and Building Materials, 20(1-2): p. 90-100.
10. **Ceroni, F., Pecce, M., Manfredi, G., Marcari, A.** (2003). "*Experimental bond behavior in masonry elements externally reinforced with FRP laminates",* in *Proceedings of International Conference Composites in Constructions*, Cosenza, Italy.
11. **Fedele, R. and Milani, G.** (2010). "*A numerical insight into the response of masonry reinforced by FRP strips. The case of perfect adhesion",* Composite structures, 92 (10): p. 2345-2357.
12. **Oliveira, D., Basilio, I., Lourenço, P.B.** (2011). "*Experimental bond behavior of FRP sheets glued on brick masonry",* Journal of Composites for Construction (in press).
13. **Wu, Z.** (2003). "*Element-level study on stress transfer based on local bond properties"*, in *Technical report of JCI technical committee on retrofit technology*.
14. **Silva, M.A.G. and Biscaia, H.** (2008). "*Degradation of bond between FRP and RC beams",* Composite structures, 85(2): p. 164-174.
15. **Benzarti, K., Chataigner, S., Quiertant, M., Marty,C., Aubagnac, C.** (2010). "*Accelerated ageing behaviour of the adhesive bond between concrete specimens and CFRP overlays",* Construction and Building Materials (In press).
16. **Subramaniam, K.V., Ali-Ahmad, M., Ghosn, M.** (2008). "*Freeze-thaw degradation of FRP-concrete interface: Impact on cohesive fracture response",* Engineering Fracture Mechanics, 75 (13): p. 3924-3940.
17. **Aiello, M.A. and Matthys, S.** (2006). "*The influence of service temperature on bond between FRP reinforcement and concrete",* in *2nd International Congress-fib*, Naples, Italy.
18. **Aiello, M.A. and Sciolti, M.S.** (2005). "*Influence of environmental agents on bond between FRP reinforcement and calcarenite ashlars",* Structural Analysis of Historical Constructions, p. 875-881.
19. **Desiderio, P. and Feo, L.** (2005). "*Durability Evaluation of EBR CFRP Strengthened Masonry Structures",* in *Proc. of BBFS*. 2005.
20. **Briccoli Bati, S. and Rotunno, T.** (2001). "*Environmental durability of the bond between the CFRP composite materials and masonry structures",* Historical Constructions, p. 1039-1046.
21. **Byras, E., Waldron, P., Dejke, V., Demis, S., Heddadin, S.** (2003). "*Durability of FRP in concrete deterioration mechanisms",* International Journal of Materials and Product Technology, 19(1-2): p. 28-39.
22. **Dai, J.G., Ueda, T., Sato, Y.** (2006). "*Unified analytical approaches for determining shear bond characteristics of FRP-concrete interfaces through pullout tests",* Journal of Advanced Concrete Technology, 4(1): p. 133-145.
23. **Nakaba, H., Kanakubo, T., Furuta, T., Yoshizawa, H.** (2001). "*Bond behavior between fiber-reinforced polymer laminates and concrete",* ACI Structural Journal, 98(3): p. 359-367.
24. **DIANA** (2009). *"Displacement analysis finite element software"*, V. 9.4, TNO Building Division, Delft, The Netherlands.
25. **Fava, G., Mazzotti, C., Poggi, C., Savoia, M.** (2007). "*Durability of FRP-concrete bonding exposed to aggressive environment",.* in *Proceedings of FRPRCS-8,* Patras, GR.
26. **CNR-DT 200** (2004). "*Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures"*, National Research Council, Rome.